On the Detectability of Very Massive Compact Objects with Gravitational Microlensing

by

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ABSTRACT

If the dark halo of our galaxy is made of compact objects as massive as $M \sim 10^6\ M_\odot$, their detection by means of ordinary microlensing searches would take a very long time as the characteristic time scale of such a lensing event is $t_0 \sim 200$ years. Fortunately, the very high magnification events of the numerous faint stars, which are normally well below the detection threshold, have short duration peaks with a characteristic time scale $t_{1/2} \sim t_0/A_{max}$, where $A_{max} \gg 1$ is the peak magnification factor. The two almost equally bright images are separated by $\sim 2''\ (M/10^6\ M_\odot)^{1/2}$, and they rotate very rapidly around the lens with the relative proper motion enhanced by a factor $\sim 2A_{max}$. The same events will offer an opportunity to study spectroscopically stars which are normally far too faint to be reached.

Key words: *black holes – dark matter – gravitational lensing*

The extension of the search for MACHOs to masses as large as $10^3 - 10^6\ M_\odot$ (cf. Lacey and Ostriker 1985) is difficult because the characteristic time scales of the microlensing events caused by them are very long, $t_0 \sim 7 - 200$ years, while the current searches are most sensitive to $10 \le t_0 \le 100$ days (Udalski et al. 1994a, Alcock et al. 1995). Even though the upper limit will gradually increase as the searches continue, it is clear that $t_0 \sim 100$ years is out of reach. In principle, one may identify such long duration events trying to uncover the very small photometric variability due to the parallactic effect (Gould 1992), but the required photometric accuracy is $\sim 1\%$, and that is very hard to achieve in a very

dense stellar field for millions of stars. However, if the impact parameter in the lensing geometry is very small, and the corresponding peak magnification is very large, $A_{max} \gg 1$, than the time scale on which the magnification changes between A_{max} and $A_{max}/2$ is only $t_{1/2} \sim t_0/A_{max}$, i.e. it may be detectable in a few years with an ordinary photometric accuracy.

The obvious problem is that the very high magnification events are very rare. However, as they bring up into visibility a huge number of very faint stars which are normally undetectable, the rate of such events may be relatively high. The aim of this paper is to study the feasibility of a search for very massive compact objects with very high magnification microlensing events of the stars in nearby galaxies. Some other problems related to microlensing of stars which are normally below the detection threshold were studied by Colley (1995), Crotts (1992), Gould (1995) and Nemiroff (1994).

A gravitational lensing system made of a point mass located at a distance D_d lensing a source star located at a distance D_s has an Einstein ring radius given as

$$\varphi_E = 0.''9 \left(\frac{M}{10^6 \ M_\odot} \ \frac{10 \ kpc}{D_d} \right)^{1/2} \left(1 - \frac{D_d}{D_s} \right)^{1/2} , \tag{1}$$

(cf. Paczyński 1986). If the relative transverse velocity of the lensing mass is V then the characteristic time scale of the lensing event is

$$t_0 = \frac{\varphi_E}{\dot{\varphi}} = 214 \ yr \ \left(\frac{M}{10^6 \ M_\odot} \ \frac{10 \ kpc}{D_d} \right)^{1/2} \left(1 - \frac{D_d}{D_s} \right)^{1/2} \left(\frac{200 \ km \ s^{-1}}{V} \right) , \tag{2}$$

where $\dot{\varphi} = V/D_d$ is the proper motion of the lens.

The magnifications of the two images formed by the lens are

$$A_{1,2} = \frac{u^2+2}{2u(u^2+4)^{1/2}} \pm \frac{1}{2}, \qquad A = A_1 + A_2 = \frac{u^2+2}{u(u^2+4)^{1/2}}, \qquad A_1 - A_2 = 1, \tag{3}$$

and their angular distances from the lensing mass are given as

$$r_{1,2} = \frac{1}{2} \left[(u^2+4)^{1/2} \pm u \right] , \tag{4}$$

where u is the angular distance between the source and the lens divided by the Einstein ring radius. Let the source move along the ‘x’ axis with impact parameter p. The coordinates of the source are given as

$$x = t/t_0, \qquad\qquad y = p = const, \tag{5}$$

where t_0 is the characteristic time scale of the lensing event defined as the Einstein ring radius divided by the source velocity, and the coordinates (x, y) are also in units of the

Einstein ring radius. We adopt $t = 0$ for the time of the peak magnification. Of course, we have

$$u^2 = x^2 + y^2. \tag{6}$$

The position angles of the two images with respect to the lensing mass are given as

$$\tan\theta_1 = \frac{x}{p}, \qquad \theta_2 = \theta_1 + \pi. \tag{7}$$

Let us consider now the case of a very high magnification, i.e. $p \ll 1$. We may expand the equations (3) and (4) and retain the leading terms to obtain:

$$A = \frac{1}{u} = \frac{1}{(p^2+x^2)^{1/2}} = A_{max}\left[1+\left(\frac{x}{p}\right)^2\right]^{-1/2}, \tag{8}$$

$$r_{1,2} = 1 \pm \frac{u}{2}. \tag{9}$$

The characteristic time scale for the brightness variation, $t_{1/2}$ is the time it takes the magnification to change from $A_{max} = 1/p$ to $A_{1/2} \equiv A_{max}/2$, i.e. by 0.76 magnitude. It follows from the eqs. (8) and (5) that

$$t_{1/2} = t_0\ x_{1/2} = t_0\ p\ \sqrt{3} = \sqrt{3}\ \frac{t_0}{A_{max}}, \tag{10}$$

i.e. $t_{1/2}$ is much shorter than t_0.

While the magnification changes from $A_{max}/2$ to A_{max} and back to $A_{max}/2$ the position angle of the first image varies from $\theta_1 = -\pi/3$ through $\theta_1 = 0$ to $\theta_1 = \pi/3$, and the rate of change is

$$\frac{d\theta_1}{dt} = \frac{\sqrt{3}}{t_{1/2}}\left[1+3\left(\frac{t}{t_{1/2}}\right)^2\right]^{-1} = \frac{\sqrt{3}}{t_{1/2}}\left(\frac{A}{A_{max}}\right)^2 = \frac{A^2}{t_0 A_{max}}. \tag{11}$$

We have the following approximate picture of a very high magnification event with a very small impact parameter, $p \ll 1$. The two images circle the lens, the primary just outside the Einstein ring, while the secondary just inside it (cf. eq. 9). Their near circular motion first accelerates while the intensity increases, and later decelerates past the light maximum (cf. eq. 11). The two images are almost equally bright. Their angular separation stays very close to the diameter of the Einstein ring, which is approximately given as

$$2\ \varphi_E = 1.''8\ \left(\frac{M}{10^6\ M_\odot}\ \frac{10\ kpc}{D_d}\right)^{1/2}, \tag{12}$$

(cf. eq. 1) where we assume that the source star is very far away, i.e. $D_d/D_s \ll 1$. Note, that if a supermassive lens is in the halo of the external galaxy, like M31, then the image separation as given with the eq. (1) is very small, as $D_d/D_s \approx 1$.

The real time discovery of the very high magnification events of stars in other galaxies will be possible when the OGLE's Early Warning System (Udalski et al. 1994b) is extended to 'new' stars, not present on the templates currently used for the rapid star identification. Once the candidate event is located the highest resolution astrometry should be attempted in order to resolve the double image. Current ground based infrared imaging achieves the resolution of $\sim 0.''2$ (Eckart et al. 1993). Even higher resolution is possible with the Hubble Space Telescope. Still higher resolution might be achieved with adaptive optics and imaging interferometry (cf. Shao and Colavita 1992, Beckers 1993, Robertson and Tango 1994, Roddier 1995, Shao 1995, and references therein). The resolution of $\sim 0.''01$ would correspond to a lensing mass of $\sim 25\ M_\odot$, and $t_0 \sim 1$ year, i.e. the range directly accessible to standard microlensing searches among the stars which are detectable at all time. Note, that if resolved, the very high magnification double image offers unmistakable evidence that it is due to microlensing: the two images rotate rapidly around the lens, with the peak relative proper motion given as

$$2\ \dot{\varphi}_{A} = 2\ \varphi_{E}\ \dot{\theta}_1 = 2\ \frac{\varphi_{E}}{t_0}\ \frac{A^2}{A_{max}} = \dot{\varphi}\ \frac{2A^2}{A_{max}}, \qquad (13)$$

where $\dot{\varphi}$ is the proper motion of the lensing object. We assume the lensed star to be so far away that its proper motion is negligible.

Direct detection of a double image would not only provide a direct proof of the microlensing event, it would also provide an estimate of the lens mass through eq. (12). In case of very high magnification events an alternative possibility to estimate the lens mass is available when the source star of a known size is resolved by the lens (Nemiroff and Wickramasinghe 1994, Witt and Mao 1994, Witt 1995). In the very rare case when the source is resolved by the lens, and at the same time the image is resolved directly, the image would appear to be not just double, but ring-like.

The obvious problem with the proposed method of extending the microlensing search to supermassive objects is the low probability of the very high magnification events. The standard optical depth τ is defined as the probability that any particular star is magnified by a factor larger than $3/\sqrt{5} \approx 1.34$ (corresponding to $u = 1$ in eq. 3). The probability that at any given time a particular star is magnified by a factor $A \gg 1$ is equal to τ/A^2. However, as the duration of each very high magnification event, $t_{1/2}$, is shorter than t_0 by a factor A, the rate of the very high magnification events is lower than ordinary events only by a factor A. Therefore, if the luminosity function below the detection threshold is inversely proportional to the stellar luminosity, i.e. the number of faint stars is larger

in inverse proportion to their luminosity, then the very high magnification event rate is independent of their magnification factor. However, for a given lensing mass the effective duration of those events, $t_{1/2}$, is inversely proportional to A_{max} (cf. eq. 10). This implies that a larger number of photometric measurements is required to reliably detect those events.

Our conclusion is: it should be possible to either detect supermassive objects in the galactic halo if those objects exist, or to put stringent upper limits on their number density, within a sensibly long observing project, like 10 years. However, it will be necessary to make frequent photometric measurements to detect the short duration peaks of very the high magnification events of faint stars which are normally below the detection threshold. It will be very helpful to have real time identification of the events with a new Early Warning System. The same project will make it possible to obtain spectra of the lensed stars, which are normally too faint to be reached.

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